STATUS OF NHTSA'S EJECTION MITIGATION RESEARCH PROGRAM

Donald T. Willke
Stephen Summers
National Highway Traffic Safety Administration
J. Stephen Duffy
Allison E. Louden
Jeffrey C. Elias
Transportation Research Center, Inc.
USA
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ABSTRACT

One of the most important problems in rollover safety is ejection mitigation. A few years ago, advanced side glazing systems appeared to be the only reasonable method for passively providing ejection mitigation. More recently, automobile manufacturers announced plans to provide ejection mitigation in some of their vehicles through the use of inflatable devices. These devices are modified versions of the inflatable head protection devices that are currently available in many vehicles. Both inflatable devices and advanced glazing systems are being examined in NHTSA's current ejection mitigation research program.

A dynamic rollover fixture (DRF) was developed as a research tool to produce full-dummy ejections more repeatably and at less cost than full-scale testing. The DRF is being used to evaluate the effectiveness of inflatable devices, advanced glazings, and combinations of these systems in reducing occupant ejections. Also, impactor tests were previously developed to measure the retention and head injury causing potential of advanced glazing systems. These test procedures are being examined to determine if they are suitable for evaluating inflatable devices and combination systems. This paper discusses the status of the agency's current ejection mitigation research program.

INTRODUCTION

Background

The National Highway Traffic Safety Administration (NHTSA) has had an active research program on ejection mitigation since the early 1990's. The research program initially studied the use of advanced side windows systems for ejection mitigation [1,2,3]. The research program involved several studies of ejection producing crashes investigated by the National Automotive Sampling System (NASS). These studies encompassed a wide variety of crash environments that have involved occupant ejection. NHTSA researchers noted that the window frames remain intact for 20 to 50 percent of ejection producing crashes. Since the doorframe provides a critical load path for occupant to glazing impact, this observation was significant for the feasibility of ejection mitigation using advanced side windows.

Film analysis of staged rollover and side impact crash tests measured the impact speed for numerous dummy-to-window contacts. Based on this analysis, a rollover contact speed of 16 kmph (10 mph) and a side impact contact speed of 24 kmph (15 mph) were established. These speeds were used in a sled test series to evaluate the forces applied to the window from occupant impacts during side impact and rollover crashes. This test series indicated that a 50th percentile male dummy exerted a force approximated by an 18 kg (40 lb) object. An 18 kg guided impactor was then developed to evaluate the retention capability of advanced side glazing systems at impact speeds from 16 to 24 kmph.

Baseline retention testing using the guided impactor was then conducted using a variety of advanced glazing systems. Several door / window encapsulation designs were also evaluated in these tests. The advanced glazing systems showed potential for ejection mitigation, but there were concerns regarding their potential for causing head and neck injuries. NHTSA conducted a second series of sled tests to evaluate dummy impacts with tempered glass, for comparison to those into advanced glazing systems. Free-motion headform tests [4] were also conducted to evaluate head responses. These tests demonstrated that the head injury potential for the advanced glazing systems appears to be similar to that for current tempered glass systems, however the potential for increasing neck injuries was unclear.

Around this time, BMW introduced the Inflatable Tubular Structure (ITS) for improving side impact protection. Conceptually, this was the first inflatable curtain-type system in production. There appeared to be a significant potential for these curtain systems to also function as ejection countermeasures. NHTSA conducted a series of five full-scale rollover tests using prototype side curtain systems from TRW and Simula. Both systems appeared to be very effective at preventing complete ejections, but there were partial arm ejections for 9 of the 10 occupants in the tests. As a result of this preliminary testing, it was decided to expand future ejection mitigation research to include both glazing and side air curtain countermeasures. This paper presents some preliminary research conducted in the expanded research program.

Problem Definition

Overview - There were 31,925 fatalities among occupants of light vehicles in 2001, and an estimated 6,031 fatalities (19 percent) were ejected through side windows. This includes 3,815 completely ejected fatalities and 2,216 partially ejected fatalities. Partial or complete ejection through side windows accounted for 3,766 fatalities in rollover crashes, or 35 percent of the rollover fatalities in 2001. From 1997 through 2001, an average of 34,963 light passenger vehicle occupants were completely ejected each year. Of these, 13,833 (40 percent) were ejected through side windows. This includes 9,862 through front-side windows, which is 28 percent of the complete ejections.

General Ejection Statistics - The 2001 Fatality Analysis Reporting System (FARS) and the 1997 through 2001 NASS were reviewed to determine the number of injuries and fatalities associated with ejection from light motor vehicles and, specifically, ejection through motor vehicle side windows. The FARS data include a report of each fatal crash that occurred on a public access road in the 50 states, the District of Columbia, and Puerto Rico. The NASS data are based on a detailed investigation of a sample of police-reported towaway crashes, conducted by 24 field research teams; NASS investigates about 5,000 light vehicle crashes a year.

Initially, all ejection-related fatalities were identified, regardless of ejection route. The 2001 FARS data include 31,925 people who were killed as occupants of cars, light trucks, passenger vans, or utility vehicles. Twenty-nine percent of these fatalities (9,258) were reported by the police to have been ejected from the vehicle; 23 percent were completely ejected, and 6 percent were partially ejected. (Partial ejection is defined as having some portion, but not all, of the occupant's body outside the motor vehicle during the crash.) The NASS data are more detailed, but they are based on a sample of cases. The annual average fatality estimate from the 1997-2001 NASS data is lower than the 2001 FARS count: 26,832 estimated from NASS compared to 31,925 counted by FARS. Both the NASS and FARS data indicate that about 23 percent of occupant fatalities were completely ejected from the vehicle, but the NASS data suggest that FARS does not identify some of the partial ejections (an estimate of 9 percent from NASS compared to the 6 percent reported to FARS).

The NASS data are most useful for showing percentage distributions of subcategories of the crash events. Therefore, in the following analyses and discussions, the total number of fatalities identified in the 2001 FARS database was used as the basis total, and percentages based on the 1997-2001 NASS fatality estimates were used for distributions of this total. The NASS estimates of non-fatal involvements were not adjusted because these represented the best estimates of annual occurrences. Also, there were some missing data in the NASS ejection reporting (unknown ejection status, degree, and route). These missing data were prorated among the known outcomes in an attempt to improve the ejection estimates and to avoid producing estimates that were too low.

In 2001, an estimated 32 percent of fatalities were partially or completely ejected through all vehicle openings (Table 1), accounting for 10,325 fatalities. Ejection rates were lower among seriously injured survivors (that is, among survivors with an Abbreviated Injury Scale (AIS) rating of 3 or greater). An estimated 10 percent of seriously injured survivors were completely ejected and 2 percent were partially ejected. About 1 percent of all occupants of light vehicles that were in towaway crashes (without regard to injury outcome) were ejected, which is an estimated 52,936 partial and complete ejections per year. This pattern was consistent with previous research. For example, Winniki [5] showed that ejection is associated with an increased risk of fatality.

Side Window Ejections - From 1997 through 2001, there were an estimated 34,963 complete ejections per year, and 13,833 (40 percent) of these were through side windows. The most common window ejection routes were the right-front and left-front windows. There were 3,360 fatalities who were completely ejected and 2,029 fatalities who were

Table 1
Ejection Status for Occupants of Light Vehicles
Annual Average for 1997-2001 NASS, Fatalities Adjusted to 2001 FARS

	Cases	**Estimate**	**Percentage**
Fatalities			
Not ejected	1,549	21,599	68%
Completely ejected	468	7,503	24%
Partially ejected	217	2,822	9%
Unknown degree	8	distributed	distributed
Unknown if ejected	23	distributed	distributed
Total	2,265	31,925	100%
Seriously-Injured Survivors			
	Cases	**Estimate**	**Percentage**
Not ejected	4,024	81,314	88%
Completely ejected	430	9,736	10%
Partially ejected	146	1,717	2%
Unknown degree	15	distributed	distributed
Unknown if ejected	51	distributed	distributed
Total	4,666	92,767	100%
All Occupants			
	Cases	**Estimate**	**Percentage**
Not ejected	46,318	5,007,950	99.0%
Completely ejected	1,461	34,963	0.7%
Partially ejected	679	17,973	0.4%
Unknown degree	50	distributed	distributed
Unknown if ejected	484	distributed	distributed
Total	48,992	5,060,886	100.0%

partially ejected through the left- and right-front side windows, which is a total of 5,389 lives lost.

Injury Outcome for Side Window Ejections - From 1997 through 2001, there were an estimated 6,031 fatalities and 3,659 seriously injured survivors ejected through side windows each year. Table 2 shows a breakdown by injury severity and ejection degree, indicating that both partial and complete ejections present a safety problem. Partial or complete ejections through light vehicle windows were associated with 19 percent of fatalities and four percent of seriously injured survivors.

Rollover versus Non-rollover crashes - From 1997 through 2001, an estimated 5,060,886 occupants were involved in light vehicle towaway crashes each year, including 469,254 in rollover crashes. There were 10,643 fatalities in rollovers in 2001. (Most of the other 21,282 fatalities in 2001 occurred in front, side, or rear crashes.) Of these rollover fatalities, 3,766 involved complete or partial ejection through side windows (Table 3).

Ejections are not unique to rollover. There were 2,265 complete and partial ejection fatalities in planar (non-rollover) crashes. A total of 6,031 people were

Table 2
Injury Severity for Ejections through Side Windows Annual Average for 1997-2001 NASS Fatalities Adjusted to 2001 FARS

	Fatalities	**Seriously-Injured Survivors**	**Lesser Injury**	**Total Injured**
Complete ejection	3,815	2,520	7,462	13,797
Partial ejection	2,216	1,139	10,138	13,493
Total	6,031	3,659	17,600	27,290

Table 3 -- Fatal Side-Window Ejections Annual Average for 1997-2001 NASS, Fatalities Adjusted to 2001 FARS

	Rollover	Planar	Total
Complete Ejection	2,496	1,319	3,815
Partial Ejection	1,270	946	2,216
Total	3,766	2,265	6,031

killed in crashes involving partial or complete ejection through side windows in 2001. Sixty-two percent of the side-window ejection fatalities occurred in a vehicle rollover and 38 percent were in non-rollover (planar crashes).

Vehicle Type - The number of ejections as a function of vehicle type were estimated. From 1997 through 2001, there were an average 52,936 partial and complete ejections per year. About 28,165 of these were through side windows. Table 4 shows higher ejection rates for pickup trucks and sport utility vehicles than for passenger cars and vans.

Belt Use Versus Ejection - Virtually all completely ejected people were unbelted. In one analysis [6] the agency determined the belt use of ejected drivers, using the 1989 FARS data. That study indicated that 98 percent of the completely ejected drivers and right front passengers were unbelted. Ninety-five percent of all occupants who were completely ejected from a light vehicle in 2001 were reported to have been using no safety belt of any type.

In order to determine the effect of increased seat belt use on the reduction of occupant ejections, two sets of data were compared. As shown in Figure 1,

Table 4
Side-Window Ejections by Vehicle Type.
Annual Average for 1997-2001 NASS, Fatalities Adjusted to 2001 FARS

	Partial Ejection	Complete Ejection	All Ejections	All Occupants in Crashes	Side Window Ejection per 1,000 Occupants
Passenger car	5,992	5,107	11,099	3,611,799	3
Utility vehicle	2,227	3,666	5,943	532,633	11
Vans	1,819	1,677	3,496	396,906	9
Pickups	4,184	3,341	7,525	512,457	15
Other/unknown	59	41	100	7,092	14
Total	14,332	13,833	28,165	5,060,886	6

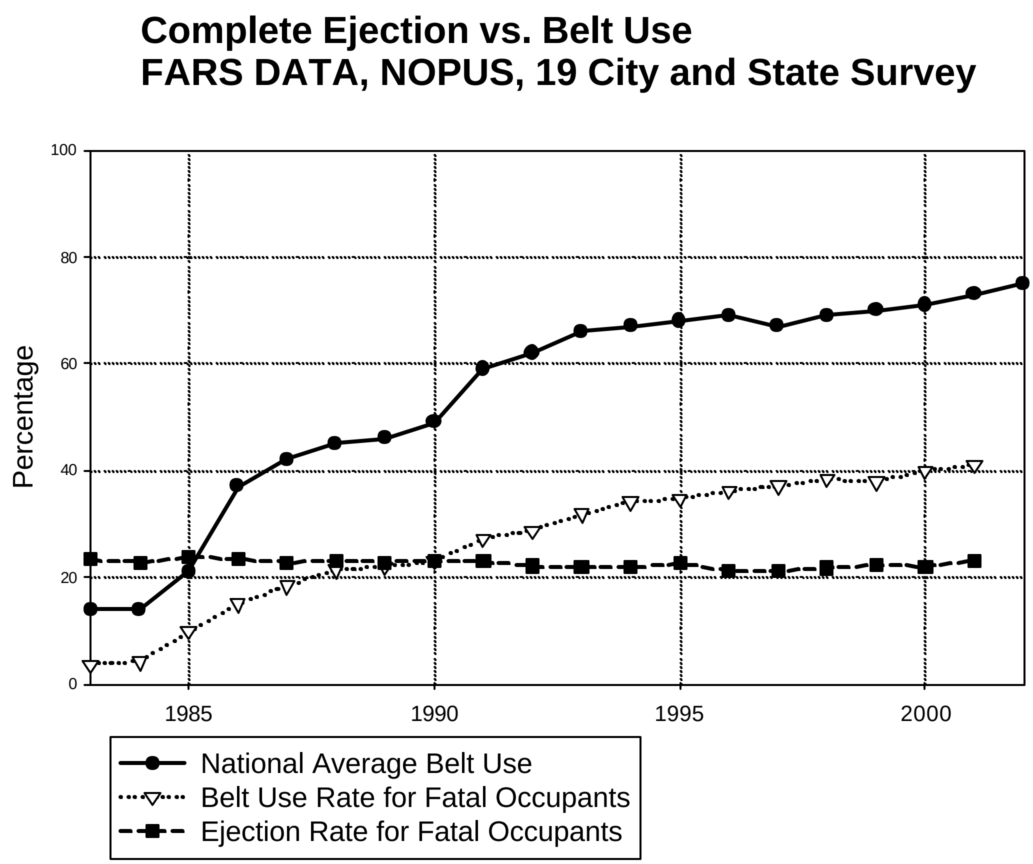

Figure 1. Belt Use Rates For Fatal And Ejected Occupants.

increased seat belt use has not caused a concurrent decrease in fatal ejections [7]. The agency has observed this phenomenon for many years. It may be due to the continued non-use of belts among drivers involved in high-speed crashes where ejection is more likely. Those occupants most likely to be involved in fatal crashes are the least likely to use a seat belt. This problem continues to be addressed by NHTSA as part of its efforts to increase seat belt use. It may also be due to the change in vehicle mix, especially the increased presence of sport utility vehicles (SUVs) on the nation's roadways. SUVs have a higher propensity for rollovers, where the risk of ejection is higher than that for planar crashes.

Objectives

There are two major research challenges for addressing ejection mitigation. First, since full-vehicle rollover crash tests are not repeatable events, it is necessary to develop component-level test(s) to evaluate the performance of potential ejection mitigation systems. The systems must be evaluated for occupant retention capability and perhaps for their potential to cause other injuries (head, neck, laceration, etc.). For a test to be acceptable, it must be shown that good (or poor) performance in the laboratory test indicates good (or poor) performance in the real world.

The second major challenge for this research program is to identify and evaluate potential countermeasures. Recently, automobile manufacturers have announced plans to provide side air curtains, in conjunction with rollover crash sensors, in some of their vehicles. The 2003 Lincoln Navigator is now available with such a system. These devices are modified versions of the inflatable head protection devices that are currently available in many vehicles.

Use of an inflatable system presents an additional challenge, in that since it would be dynamically deployed during a crash, a rollover sensing system is required. The sensing system must not only predict that a rollover will occur, but it must do so early enough to allow the inflatable device to deploy between the occupant's head and the side window. This is particularly challenging since in many crashes, the rollover event is preceded by significant lateral vehicle deceleration, which effectively throws the occupant toward the window.

DYNAMIC ROLLOVER FIXTURE

Description and Operation

Full-scale rollover crash tests are complex and costly events, often producing non-repeatable occupant kinematics. Consequently, there exists a need for a testing method that can replicate occupant kinematics in a controlled and repeatable way. The Dynamic Rollover Fixture (DRF) is a research tool designed to produce repeatable, full-dummy ejections in a less costly manner than full-scale testing.

The DRF is modified from a previous NHTSA test device known as the Rollover Restraint Tester (RRT) [8] that models a rollover condition in which the vehicle becomes airborne at the initiation of roll, then impacts on the roof structure after rotating approximately 180 degrees. The DRF rotates approximately one revolution and is brought to rest through the application of a pneumatic braking system on one end of the pivot axle.

The main features of the DRF consist of 1) the support framework, 2) a test platform with a pivot axle, and 3) a drop tower and free weight assembly (see Figure 2). The support framework is rigidly attached to the floor and braced to minimize any movement of the structure. The drop tower and free weight system provides the driving force for the DRF. A cable attached to the suspended weight is routed through a system of pulleys and spooled around large circular plates attached to the front and back of the platform. The radius of the circular plates provides the moment arm for the suspended weight to act upon in order to accelerate the platform. An array of nine standard automotive piston shocks is used to slow the free weight at the end of the drop. The angular velocity of the DRF can be modified by varying the mass (force generating the acceleration) and/or the drop height (duration of the acceleration pulse) of the free-weight. For testing reported in this paper, both weight and height were held constant which generated angular velocities between 330 and 360 degrees per second.

A test buck was fabricated from a Chevrolet C/K pickup cab by dividing the cab longitudinally down the center from the firewall to the B-pillar. The left (driver) side was then rigidly attached to the test platform. This particular vehicle model was chosen so that the advanced glazing systems developed in previous ejection mitigation research [3] could be evaluated as to their effectiveness in mitigating ejection. A generic bench seat was used to allow the dummy's initial seating position to vary with respect to the side door/window. The seat back and cushion were fabricated from Teflon®, which minimized the shear forces on the dummy buttocks and allowed the more desired loading on the window area by the head and upper torso.

Figure 2. Dynamic Rollover Fixture

For testing reported in this paper, two dummy positions were used. The first position was behind the steering wheel. For the second position, the dummy was moved inboard (toward the pivot axle) which generated higher contact velocities. Film analysis was used to measure the dummy's relative head contact velocity with the side window plane from these two designated seating positions, for both the Hybrid III 50th percentile male and 5th percentile female dummies. From the behind the steering wheel position, these impact speeds were 14 kmph (9 mph) for the 5th female and 18 kmph (11 mph) for the 50th male. From the inboard position, the velocities were 31 kmph (19 mph) for the 5th female and 29 kmph (18 mph) for the 50th male.

The test buck's lateral position from the pivot axle can be adjusted as required. Since the mass moment of inertia of the system is sensitive to the lateral positioning of the buck, different dummy trajectories and initial vehicle contact points can be obtained. Reducing the roll radius increases the initial angular acceleration for a given drop weight. Two positions were used in testing to date. For most of the tests, the cab was mounted such that the driver side door beltline was 147 cm (58 in) from the pivot angle. For a limited number of tests, the cab was positioned 56 cm (22 in) closer to the pivot axis to shorten the radius of rotation.

The yaw angle between the test buck and test platform can also be adjusted to produce different occupant-to-window area impact locations. Rotating the buck counter clockwise with respect to platform results in dummy contact at the window area near the A-Pillar.

The DRF simulates only the rotational component of the rollover event. Because the DRF does not simulate the vertical height and velocity component of the rollover event, it is difficult to analyze any potential change in an ejection countermeasure's performance due to a direct roof impact and the resulting deformation that may occur. In addition, because the pre-roll event linear accelerations are not simulated, an evaluation of a rollover sensor may be limited.

Ejection Countermeasure Candidates

Three ejection countermeasures are being examined: two experimental roof rail mounted inflatable devices and advanced side glazings developed under previous NHTSA research. The systems are being evaluated for their effectiveness both as stand-alone devices and as combination systems (air bag plus advanced side glazing).

The first inflatable device is the Advanced Head Protection System (AHPS®) developed by Simula Automotive Safety Devices, Inc. (see Figure 3). This device consists of the integration of their Inflatable Tubular Structure (ITS) [9] integrated with a cloth sleeve. The sleeve provides additional covering of the window area. Like the ITS, the AHPS is not vented and remains inflated for up to seven seconds. Although the system used in this testing was tailored for the Chevrolet C/K test buck, the AHPS is currently available in some vehicles.

The second inflatable device is an experimental air bag developed by TRW. The air bag is fixed to the A- and B-pillar at its end points and along the roof rail. The system is made of a low permeable material liner that allows the unit to remain inflated for more than six seconds. When fully deployed, the air bag covers most of the window area (see Figure 4).

Figure 3. Advanced Head Protection System (Simula)

Figure 4. Prototype Window Curtain (TRW)

The advance side glazing systems include experimental bilaminate glazing, consisting of standard C/K tempered glass (4.0 mm) with a 0.9 mm plastic film bonded to inner surface, and a laminate construction, similar to windshields, consisting of two 1.84 mm heat-strengthened glass plys sandwiching a 0.76 mm polyvinyl butyral (PVB) film. The entire window edge is encapsulated. For the testing described in this paper, door/window frame modifications were made to the C-channel along the vertical sides (A and B-pillar), and for some, modifications were also made to the top and diagonal sides.

Test Matrix

A series of tests is being conducted to determine the effectiveness of experimental roof rail mounted inflatable devices, advanced side glazing, and combinations of these systems in retaining occupants during rollover type crashes. The testing is also evaluating the countermeasures' potential for head and neck injury. The matrix of tests conducted and reported in this paper is shown in the Appendix.

Unrestrained 50^{th} percentile male and 5^{th} percentile female Hybrid III dummies were instrumented with 6-axis upper neck load cells and tri-axial accelerometers in the head. Tethers were loosely attached to the dummy's spine box and ankles to prevent full excursion outside the buck and damage to the instrumentation cables. High-speed cameras were rigidly attached to the test buck in front of the dummy for a close view of the dummy's head and torso relative to the side window and on the side to show the full dummy kinematics. A Systron-Donner roll rate sensor measured the angular velocity about the roll axis.

Test Results

General Kinematics - Dummy kinematics were dictated by the actions of gravitational and rotational forces. As the platform rotated through 90 degrees, very little movement of the dummy toward the "interior" of the test buck was seen. As the angular velocity for the platform increased, the normal and tangential accelerations (rotational forces) created by the rotational motion began to increase. The normal acceleration caused a centripetal force outward from the center of rotation. As a result of this force, the dummy had a steadily increasing tendency to move outwards towards the side door/window. The tangential acceleration imparted a force through the test buck seat that caused the unrestrained dummy to rise from seat as it moved outward. The dummy's upper portion (head, neck, upper torso) loaded the countermeasure, if present, while the lower body loaded the door.

Moving the test buck closer to the axis of rotation increased the angular acceleration that in turn imparted a greater tangential force on the dummy, causing the dummy to rise further from the seat. Testing with the 5^{th} female dummy at this reduced roll axis produced head/torso contact higher on the window area resulting in more of the dummy loading the countermeasure. In similar testing with the 50^{th} male dummy, the head struck the roof rail prior to contact with the countermeasure preventing any further outward motion.

Baseline Testing - Baseline testing was conducted with an open side window to determine if the DRF could produce fully body ejections. In testing with the buck positioned farthest from the roll axis, film analysis showed that the dummy's lower torso and pelvic area loaded the side door while the head and upper torso crossed the side window plane between 90 and 180 degrees from the initiation of roll. As the buck continued to rotate, the lower torso and pelvis slid up along the door and the dummy was fully ejected (see Figure 5). This was the general kinematics for the 50th and 5th dummies in both seating positions. When the buck was moved closer to the roll axis, the 5th female rose higher out of the seat resulting in more lower torso loading of the window initially. Full ejection was eventually achieved in this testing configuration, as well. By removing the interior components of the C/K test buck, the dummies did not experience random movements due to contact accelerations. As a result, the tests exhibited repeatability, thus providing a method to evaluate a countermeasure's ability to contain an occupant.

Figure 5. Full Ejection Through Open Window

Inflatable Device Testing - In the testing of inflatable devices reported in this paper, the air bags were pre-deployed and their set pressure was maintained throughout the test by the use of an air reservoir tank mounted on the platform. Prior to contact with the door, the dummy kinematics and lower body loading in tests with both of the inflatable devices were similar to those described for the baseline tests. At that point, the upper body loaded the inflatable device, limiting the dummy's vertical movement toward the roof. This caused the pelvis to load the side door throughout the roll, rather than to ride up the door as was seen in the baseline tests. The inflatable devices contained the torso, head, and neck of the dummy, so complete ejection did not occur. However, both the devices did allow the shoulder and arm to escape below the bags, resulting in partial ejection. One example of this is shown in Figure 6.

Advanced Side Glazing System Testing - Limited testing was conducted with stand-alone advanced side glazing systems. The testing reported here involves the laminated candidate with door/window frame modifications around the entire periphery, as reported in reference 3. This advanced glazing system contained the 50th male and 5th female dummies entirely inside the test buck. Loading of the glazing flexed the window frame, producing a gap between it and the roof rail, with the gap size dependent on the dummy size. In the test involving the 50th male located behind the steering wheel, the dummy's shoulder shattered the glass. However, the glazing system remained entirely inside the modified door frame, and no tearing of the plastic interlayer occurred. Total integrity of the system was seen (no glass breakage) under loading conditions involving the 5th female, from both designated seating positions.


Figure 6. Partial Ejection Below Air Bag

Combination Systems Testing - Limited testing was also conducted on the inflatable devices used in combination with the laminated side glazing candidate. In this configuration, the door/window frame modifications involved only the vertical C-channels at the front and rear. The top and diagonal encapsulated glazing edges were flush up against the window frame and could dislodge from the frame with direct loading. Film analysis showed that in every test conducted, the dummy remained entirely inside the test buck. Although the shoulder and arm escaped under the inflatable devices, the advanced glazing remains in the doorframe, preventing the upper extremity from passing beyond the plane of the window.

Dummy Responses - Head and neck dummy responses are tabulated in the Appendix. The numbers listed are the peak values recorded due to contact with the test buck interior compartment or the countermeasure, from the initiation of roll throughout the engagement with the countermeasure. Note that there were no interior trim components on the test buck. In some cases, higher injury values were obtained from contact with the test buck after the dummy rebounded from the countermeasure, but those are not include in the table. The HIC_{36} and axial neck loads (compression and tension) can be evaluated against IARVs established in Federal Motor Vehicle Safety Standard numbers 201 and 208 [10,11], respectively (see Table 5). The lateral neck loads and moments are used to show trends only, since established IARVs do not exist. The moments listed in the Appendix are those measured by the upper axial neck load cells and were not translated to the occipital condyle.

Table 5
Injury Assessment Reference Values

	HIC_{36}	Upper Neck Tension (N)	Upper Neck Compression (N)
5th Female	1000	2620	2520
50th Male	1000	4170	4000

Based on the testing reported in this paper, the risk of head or neck injuries appears to be relatively low when the various ejection countermeasures were used. The highest HIC_{36} response recorded was 90, which occurred in an open window test. Also, tension loads on the neck were quite low, as the maximum for all tests was only 35 percent of the IARV. Compression loads on the neck were generally somewhat higher, although most were below 40 percent of the IARV. Three of the tests with the 5th female exceed this level, recording compressive neck loads of 48, 70, and 82 percent of the IARV. Three of the tests with the 50th male were above the 40 percent level, although all these were below 60 percent of the IARV. In each of these cases, the peak neck load was due to contact with the side roof rail of the test buck, while the dummy was engaged with the countermeasure.

The presence of a countermeasure generally resulted in higher lateral neck loading on the dummy. For the 50th male, the lateral shear loads ranged from 290 to 327 N (65 to 74 lb) in the open window tests, and they ranged from 315 to 950 N (71 to 214 lb) in tests with a countermeasure. For the 5th female, they ranged from 221 to 329 N (50 to 74 lb) in the open window tests, and they ranged from 161 to 1020 N (36 to 229 lb) in tests with a countermeasure. Similarly, the lateral bending moments for the 50th male ranged from 16 to 19 N-m (142 to 168 in-lb) in the open window tests, and they ranged from 26 to 61 N-m (230 to 540 in-lb) in tests with a countermeasure. For the 5th female, they ranged from 14 to 19 N-m (124 to 168 in-lb) in the open window tests, and they ranged from 13 to 53 N-m (115 to 469 in-lb) in tests with a countermeasure. The highest shear load and moment seen for the 5th female both occurred in a test from the inboard dummy position and into the laminated glazing. For the 50th male, the highest shear load and moment both occurred in a test from the inboard dummy position and into the TRW air curtain. As stated previously, due to the lack of established IARVs, the risk of injury associated with the lateral neck shear loads and bending moments encountered in these tests is unknown.

GUIDED IMPACTOR

Description

The DRF described in the previous section is a useful research tool for evaluating the ejection mitigation capabilities of various countermeasures. It is not believed to be a viable test for compliance or regulatory purposes, if NHTSA were to pursue a regulation in this area. Therefore, the guided impactor developed for use with advanced glazing systems is under evaluation as a possible occupant retention test for a wider variety of ejection mitigation systems.

The details of the development of this impactor are contained in reference 3. In brief, it consists of an 18 kg mass guided by four rails (see Figure 7). An existing featureless free-motion headform was selected for the impactor face. This rigid headform, covered with a headskin, was originally designed for the upper interior head protection research program. It averages the dimensional and inertial characteristics of the frontal and lateral regions of the head into a single headform [12]. Since it is a guided impactor, only uni-axial motion is measured, and it is capable of measuring dynamic deflection during an impact. The propulsion unit is based on a device developed by the General Motors Corporation [13], scaled up to accommodate the heavier mass. The impactor can be placed inside the vehicle for testing the side window areas, and it can be positioned to strike different locations in those areas.

Test Matrix

The DRF evaluates the full-dummy occupant retention capabilities of ejection mitigation systems. Guided impactor tests are conducted to determine if they can predict the same performance as the DRF tests. The level of performance measured by the guided impactor, though, can vary depending on the impact locations and speeds used. Therefore, a matrix of guided impactor tests was developed which compliments the DRF tests described previously (see Table 6). The primary goals of these tests are to determine if the guided impactor is a suitable device for measuring the occupant retention performance of a variety of possible countermeasures, and if it is, to measure that performance under various impact conditions (location and speed).

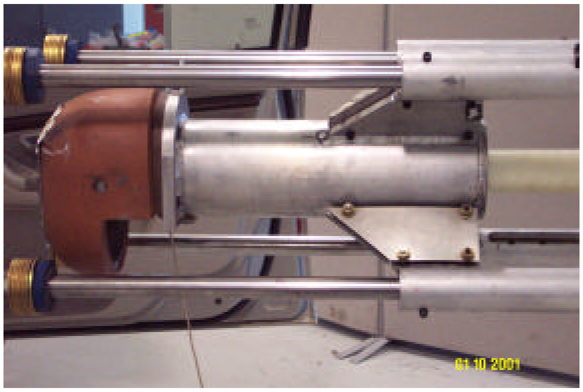

Figure 7. 18 kg Guided Impactor.

There was extensive testing of advanced glazing systems in earlier stages of this research program, and those results were reported in reference 2. Several different systems were tested using the guided impactor, at two different impact locations, and at speeds ranging from 16 to 24 kmph. In summary, the systems evaluated in that study were capable of containing the 18 kg mass at speeds up to 24 kmph, when appropriate encapsulation methods and door modifications were used. The excursion of the impactor beyond the plane of the vehicle window ranged from about 100 to 250 milllimeters.

Since considerable testing of advanced glazing systems has already been done, the current effort is focused on the testing of inflatable systems alone and in combination with glazings. Based on that earlier work, the current test matrix includes testing at up to four impact locations and at impact speeds of 20 and 24 kmph. The actual inpact locations have not yet been reported, but may include one or both of those used in the earlier testing of advanced glazings. The systems that will be tested include those being evaluated with the DRF, but will likely include some additional systems.

Table 6.
Guided Impactor Test Matrix

	Impact Location on Side Window Area							
	1		2		3		4	
	20 kmph	24 kmph	20 kmph	24 kmph	20 kmph	24 kmph	20 kmph	24 kmph
Advanced Glazing Systems Only								
Inflatable Systems Only								
Inflatable Systems With Glazing (pre-broken)								
Inflatable Systems With Glazing (unbroken)								

Test Results

At this point in time, few of the tests outlined in Table 6 have been conducted. Based on limited testing, inflatable systems appear to be capable of containing the impactor at 24 kmph, with little excursion beyond the plane of the vehicle window, when impacted at certain locations. At other locations, such as those not sufficiently covered by the air bag, they are not able to stop the impactor before the limits of its travel are reached (about 150 mm beyond the plane of the vehicle window, depending on test set-up). When combined with advanced glazings (pre-broken and with only vertical edge capture), they may be able to contain the impactor at 24 kmph at a larger range of impact locations.

These results, when compared to the results of the DRF tests, indicate that the guided impactor may be a suitable device for evaluating the occupant retention capability of a variety of ejection mitigation systems. Since the impactor face loads a more concentrated area than that of the full dummies in the DRF tests, the guided impactor is potentially a more stringent test device than the DRF. The stringency of the test can be varied by the selection of impact areas and impact speed, as well as by the amount of allowable excursion beyond the plane of the vehicle window.

SUMMARY OF FINDINGS

The following is a summary of the findings to date from the NHTSA's ejection mitigation research program:

- Ejection through side windows is a major cause of death in automotive crashes. About one-third of all fatalities are ejected, accounting for over 10,000 deaths each year. Of these, about 58% are ejected through side windows.
- The Dynamic Roll Fixture (DRF) was developed as a research tool to produce repeatable, full-dummy ejections through an open window. As such, it can be used to evaluate the occupant retention capability of various ejection mitigation systems. It also allows for the measurement of dummy head and neck responses.
- The DRF produces realistic roll rates and occupant-to-glazing impacts speeds. Roll rates up to 360 degrees per second have been achieved, which are similar to those measured in rollover crash tests. Impact speeds ranging from 15 to 30 kmph can be obtained, depending on the dummy size and initial position. These speeds are similar to those estimated from film analysis of full-scale crash tests.
- The DRF configuration can be varied, along with dummy size and initial position, to achieve different occupant trajectories and occupant-to-window area impact locations.
- The DRF does not simulate the lateral vehicle accelerations often encountered in a rollover crash prior to the initiation of the rollover event.
- The inflatable systems show good potential for mitigating full-body ejections, although they may be susceptible to partial ejection of arms below the air bag.
- The combination of inflatable systems and advanced glazings shows good potential for mitigating full-body ejections and the partial ejection of arms below the air bag.
- The ejection mitigating systems tested have a low potential for producing head injury. HIC_{36} responses in the DRF tests ranged from 8 to 90, with the maximum occurring in an open window test.
- The ejection mitigating systems tested did not show high potential for producing injury due to axial neck loading. The maximum tension load obtained was just 35 percent of the IARV, and most of the compressive loads were less than 40 percent. Of the six tests that produced responses above that level, four were below 60 percent, while the other two were 70 and 82 percent.
- DRF tests with an ejection mitigating countermeasure produced maximum lateral neck shear loads of 950 N (50^{th} male) and 1020 N (5^{th} female) and maximum lateral bending moments of 61 N-m (50^{th} male) and 53 N-m (5^{th} female). Since there are no established injury criteria for these measures, no assessment of injury potential can be made at this time.
- The guided impactor may be a suitable device for evaluating the occupant retention capability of a variety of ejection mitigation systems.
- The guided impactor is potentially a more stringent test device than the DRF, since the impactor face loads a more concentrated area than that of the full dummies in the DRF tests. The stringency of the test can be varied by the selection of impact areas and impact speed, as well as by the amount of

allowable excursion beyond the plane of the vehicle window.

- Based on limited tests, inflatable systems appear to be capable of containing the impactor at 24 kmph, with little excursion beyond the plane of the vehicle window, when impacted at certain locations. At other locations, such as those not sufficiently covered by the air bag, they are not able to contain the impactor. When combined with advanced glazings, they may be able to contain the impactor at 24 kmph at a larger range of impact locations.

ONGOING RESEARCH

The research discussed in this paper is ongoing. While a considerable number of DRF tests have already been performed, that work will continue. The evaluation of full-dummy retention capability and injury causing potential of advanced glazing, inflatable, and combination systems will continue. This will include some testing with belted dummies, as well as unbelted.

Much of the effort will be placed on the evaluation with the guided impactor, as most of the testing shown in Table 6 had not been performed as of the drafting of this paper. The performance of a variety of ejection mitigation systems will be examined, as measured by the guided impactor, at various impact locations and speeds. This will include evaluating systems already in production, such as the 2003 Lincoln Navigator. This vehicle is equipped with inflatable curtains designed to offer occupant protection in rollover crashes, and includes a rollover sensing systems to deploy the curtain in the event of a rollover. The vehicle also has laminated side windows.

The ongoing research will also examine rollover sensing systems. This includes evaluating existing methods and/or developing new methods for measuring the performance of the systems, as well as studying the actual performance of them.

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APPENDIX

		Dummy Position	Test Number	HIC 36	Axial Compression N (% IARV)	Axial Tension N (% IARV)	Lateral Shear N	Lateral Bending N-m
Open Window	50th Male	Behind Wheel	DRF_20	43	447 (11%)	862 (21%)	327	19
			DRF_29	34	0 (0%)	723 (17%)	290	19
			DRF_30	55	0 (0%)	972 (23%)	296	16
		Inboard	DRF_21	No Dummy Response Data				
	5th Female	Behind Wheel	DRF_38	25	32 (1%)	601 (23%)	221	14
			DRF_43	41	51 (2%)	623 (24%)	268	15
		Inboard	DRF_44	69	0 (0%)	818 (31%)	329	19
			DRF_45	90	172 (7%)	871 (33%)	307	17
TRW Air Curtain	50th Male	Behind Wheel	DRF_17	8	325 (8%)	292 (7%)	638	42
			DRF_32	22	181 (5%)	314 (8%)	643	43
			DRF_33	10	282 (7%)	238 (6%)	716	35
		Inboard	DRF_34	11	730 (18%)	918 (22%)	790	45
			DRF_35	30	1176 (29%)	1123 (27%)	950	61
	5th Female	Behind Wheel	DRF_36	No Dummy Response Data				
			DRF_37	22	617 (24%)	375 (14%)	511	20
		Inboard	DRF_46	15	697 (28%)	757 (29%)	754	35
			DRF_47	13	614 (24%)	650 (25%)	729	36
			DRF_51*	15	352 (14%)	345 (13%)	668	42
Simula AHPS	50th Male	Behind Wheel	DRF_68	15	1247 (31%)	409 (10%)	450	26
			DRF_69	16	1126 (28%)	427 (10%)	344	31
		Inboard	DRF_70	19	2203 (55%)	1075 (26%)	315 ??	60
			DRF_71	21	2369 (59%)	494 (12%)	388 ??	52
	5th Female	Behind Wheel	DRF_60	10	0 (0%)	283 (11%)	447	29
			DRF_61	12	0 (0%)	290 (11%)	491	30
		Inboard	DRF_62	15	0 (0%)	605 (23%)	586	33
			DRF_63	20	0 (0%)	537 (20%)	572	35
Advanced Glazing (Laminated Glazing)	50th Male	Behind Wheel	DRF_72	84	2084 (52%)	364 (9%)	667	49
		Inboard	Test Not Yet Conducted					
	5th Female	Behind Wheel	DRF_64	57	895 (36%)	307 (12%)	200	19
		Inboard	DRF_67	50	1770 (70%)	909 (35%)	1020	53
Combination: TRW Air Curtain/Laminated Glass	50th Male	Behind Wheel	Test Not Yet Conducted					
		Inboard	Test Not Yet Conducted					
	5th Female	Behind Wheel	DRF_80	34	310 (12%)	260 (10%)	338	13
			DRF_82*	27	345 (14%)	147 (6%)	237	14
		Inboard	DRF_81	10	731 (29%)	413 (16%)	442	29
			DRF_83*	9	1220 (48%)	564 (22%)	630	13
Combination: Simula AHPS/Laminated Glass	50th Male	Behind Wheel	Test Not Yet Conducted					
		Inboard	Test Not Yet Conducted					
	5th Female	Behind Wheel	DRF_84	13	351 (14%)	220 (8%)	317	24
			DRF_86*	10	576 (23%)	265 (10%)	161	14
		Inboard	DRF_85	21	2060 (82%)	525 (20%)	385	22
			DRF_87*	10	743 (29%)	452 (17%)	223	24

* Dummy Positioned Closer to Steering Wheel with Foam Block Spacer